



MORPHOMERISTIC VARIABILITY OF *Piaractus mesopotamicus* IN ESTUARINE ENVIRONMENTS OF THE GULF OF GUINEA: IMPLICATIONS FOR STOCK IDENTIFICATION AND MANAGEMENT

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ABSTRACT

Morphomeristic analyses, integrating morphometric measurements and meristic counts, remain indispensable for stock identification, population differentiation and ecological assessment in fisheries science, particularly in data-limited regions such as West Africa. This review synthesizes classical and contemporary literature on conceptual foundations, methodological approaches and applied relevance of morphomeristic studies, focusing on Gulf of Guinea estuarine ecosystems. The study examined *Piaractus mesopotamicus* (pacu), a South American characid increasingly introduced for aquaculture diversification, as a model for investigating morphological adaptation under novel estuarine conditions. Patterns of phenotypic plasticity, environmentally mediated morphological variation and complementary utility of morphometric and meristic traits in stock discrimination are critically evaluated. The synthesis highlights how estuarine environmental gradients including salinity, hydrodynamics, and anthropogenic pressures drive morphological differentiation in fish populations and how integrated morphomeristic frameworks effectively delineate management units where genetic data are scarce. For introduced *P. mesopotamicus* populations in Nigerian estuaries, establishing morphomeristic baselines is essential for monitoring adaptation, assessing ecological integration and informing risk management. The review underscores the relevance of multivariate statistical techniques PCA, DFA, cluster analysis and allometric corrections for robust population discrimination. Applications span fisheries management enabling stock specific conservation measures and aquaculture development, supporting broodstock selection and strain characterization. Key research gaps include limited baseline data, insufficient integration of environmental covariates and underutilization of advanced morphometric approaches for non-native species in West African estuaries. Strengthening morphomeristic research on introduced fishes will enhance evidence-based decision making for sustainable exploitation, responsible aquaculture expansion and ecosystem-based management in dynamic Gulf of Guinea estuarine systems.

Keywords: Morphometrics; Meristic; Stock identification; Estuaries

INTRODUCTION

Understanding population structure, phenotypic variability and adaptive capacity of fish populations is central to sustainable fisheries management and aquaculture development (Cadrin, 2020; Jawad *et al.*, 2022). Morphomeristic studies, which integrate morphometric measurements and meristic counts, have historically provided the foundation for fish taxonomy, systematics and population biology (Damora *et al.*, 2024). Although molecular techniques now offer high-resolution insights into population genetics, morphomeristic approaches remain indispensable due to their affordability, simplicity and applicability to both historical and contemporary datasets (Swain & Foote, 1999; Loxdale *et al.*, 2017; Cadrin, 2020).

In West Africa, where fisheries are critical for food security and livelihoods, access to molecular facilities is often limited. Consequently, morphomeristic tools remain the primary means of assessing stock structure, ecological adaptation and management units in inland and estuarine fisheries (Nwachi & Egbuchunam, 2021; Asuquo & Ifon, 2022). The increasing introduction of non-native species for aquaculture diversification has intensified the need for reliable, field-applicable assessment methods. Among these species, *Piaractus mesopotamicus* (Holmberg, 1887) has gained attention due to its fast growth, omnivorous feeding habits and tolerance of variable water quality (Kubitza, 2019; Mikkola, 2024).

The establishment of *P. mesopotamicus* in estuarine environments of the Gulf of Guinea raises important questions regarding morphological plasticity, population differentiation and ecological integration. Estuaries in this region, including

the Ovia, Ugbokodo and Qua Iboe systems of Nigeria, are characterized by strong salinity gradients, hydrodynamic variability, and increasing anthropogenic pressure (Hernández *et al.*, 2021; Emeka *et al.*, 2023). This review critically synthesizes global and regional literature on morphomeristic studies with explicit focus on their application to estuarine fishes of the Gulf of Guinea and implications for introduced *P. mesopotamicus* populations.

MATERIALS AND METHODS

Morphomeristic Studies in Fisheries

Morphomeristic studies combine morphometric traits continuous measurements of body dimensions and meristic traits count of discrete anatomical features to capture phenotypic variation within and among fish populations (Oyebola *et al.*, 2024; Mohammadi-Sarpiri *et al.*, 2021). Morphometrics quantify attributes such as standard length, body depth, head length, and fin dimensions, while meristics include fin ray counts, scale rows and vertebral numbers (Ehemann *et al.*, 2024).

Historically, these approaches underpinned classical ichthyology and systematics, forming the basis for species descriptions and identification keys. Over time, their application expanded to population-level studies with the integration of multivariate statistical techniques, enabling discrimination of stocks occupying different geographic regions or ecological niches Franklin *et al.*, 2023). In fisheries science, a stock is defined as a population sufficiently discrete in space or time to be managed as a unit (Mahfuj *et al.*, 2023). Accurate stock identification is therefore fundamental to sustainable exploitation and biodiversity conservation.

In the Gulf of Guinea, morphomeristic approaches are particularly valuable due to the complex connectivity of estuarine systems and the limited availability of genetic data for many species. Studies on tilapias, croakers, and catfishes have demonstrated that morphometric and meristic traits can effectively reveal population structuring along salinity and hydrological gradients (Asuquo & Ifon, 2022; Otogo *et al.*, 2025). For introduced species such as *P. mesopotamicus*, morphomeristic frameworks provide an essential baseline for evaluating adaptation and potential ecological impacts.

Fish Morphological Variation

Morphological variation in fishes arises from interactions among genetic differentiation, phenotypic plasticity, and allometric growth (Akpomughe *et al.*, 2023; DeLorenzo *et al.*, 2022; Eriegha *et al.*, 2024). Genetically based variation reflects long-term evolutionary processes such as selection, gene flow, and drift, often associated with population isolation or persistent environmental differences (Bernatchez, 2016; Nwachi, & Dasuki, 2025).

A study by Turko & Rossi, (2022) infer that phenotypic plasticity, however, allows a single genotype to produce different phenotypes in response to environmental conditions, enhancing survival in heterogeneous habitats. In estuarine environments, where salinity, temperature, and hydrodynamics fluctuate widely, plastic responses in body shape, fin size, and head morphology are especially pronounced (Cabral *et al.*, 2025).

Allometric growth further complicates morphological interpretation, as body proportions change with size and age. Without appropriate size correction, observed differences may simply reflect ontogenetic variation rather than true population differentiation (Reist, 1985; Ohwerhi & Nwachi, 2024). Consequently, allometric adjustment and size standardization are essential components of morphometric analysis. Meristic traits, while influenced by environmental conditions during early development, are generally fixed thereafter and thus provide relatively stable indicators of population structure (Zhelev *et al.*, 2022).

Morphometric Techniques and Multivariate Analyses

Traditional morphometric analyses rely on linear measurements taken between homologous anatomical landmarks (Strauss & Bookstein, 1982). To isolate shape variation from size effects, several transformation techniques have been developed, including ratio methods, logarithmic transformations, and allometric scaling (Reist, 1985). Among these, allometric methods are widely preferred because they account for differential growth of body parts.

Multivariate statistical techniques are central to morphometric population studies. Principal Component Analysis (PCA) reduces dimensionality and identifies major axes of variation, often separating size-related from shape-related components (Jolliffe, 2002; Nwachi, 2025). Discriminant Function Analysis (DFA) assesses the ability of measured traits to correctly classify individuals into predefined populations (Thia, 2023). Cluster analysis further visualizes relationships among populations based on morphological similarity (Miranda, 2024).

In West African estuaries, PCA and DFA have been successfully applied to discriminate fish populations across environmental gradients, although classification accuracy based on morphometrics alone is sometimes limited by phenotypic overlap (Asuquo & Ifon, 2022; Ibrahim *et al.*, 2023). This limitation highlights the importance of integrating morphometric and meristic datasets for robust stock identification.

RESULTS AND DISCUSSION

Meristic Traits and Stock Differentiation

Meristic traits, including fin ray counts and scale rows, are determined during early ontogeny and remain fixed throughout the life of the fish (Larsen, 2024). Although environmental factors such as temperature and salinity during embryogenesis can influence these traits, their relative stability makes them valuable indicators of long-term population differentiation (Joseph *et al.*, 2025).

Empirical studies in tropical estuaries demonstrate that meristic traits often provide clearer population discrimination than morphometric traits alone (Singh *et al.*, 2023). In the Gulf of Guinea, fin ray counts have proven effective in distinguishing populations of tilapias and croakers across estuarine systems (Adite *et al.*, 2019; Asuquo & Ifon, 2022). For introduced species such as *P. mesopotamicus*, establishing meristic baselines is critical for monitoring population changes and maintaining broodstock integrity in aquaculture.

Estuarine Ecosystems of the Gulf of Guinea and Morphological Adaptation

Estuarine ecosystems along the Gulf of Guinea represent dynamic transitional zones between freshwater and marine environments and rank among the most biologically productive aquatic systems in Africa. These estuaries support extensive artisanal fisheries, provide critical nursery and spawning habitats for finfish and shellfish and contribute substantially to coastal food security and livelihoods (Blaber *et al.*, 2022). Their productivity is driven by high nutrient inputs from riverine discharge and tidal mixing, which enhance primary and secondary production. However, this ecological importance is increasingly undermined by multiple stressors, including urban and industrial pollution, oil exploration, sand dredging, mangrove deforestation and hydrological alteration linked to climate change and upstream damming (Hernández *et al.*, 2021; Kennish, 2023).

A defining feature of Gulf of Guinea estuaries is their pronounced environmental variability. Fish populations are exposed to fluctuating salinity regimes, changes in turbidity, oxygen availability and temperature, as well as strong tidal currents and seasonal freshwater inflows. Such environmental heterogeneity imposes strong selective pressures, shaping phenotypic traits that enhance survival and fitness. Consequently, fishes inhabiting these systems often display marked morphological plasticity and local adaptation.

Morphological adaptations in estuarine fishes are closely associated with swimming performance, feeding strategies and osmoregulatory efficiency. Hydrodynamic conditions, particularly tidal currents and variable flow velocities, favor streamlined body forms, reduced drag and robust caudal peduncles that enhance propulsion and maneuverability. Species occupying high-energy channels often exhibit elongated bodies and narrow caudal regions, whereas individuals from sheltered creeks and mangrove-lined habitats tend to display deeper bodies and enhanced stability. Feeding diversity within estuaries further influences head shape, mouth orientation, and jaw robustness, reflecting adaptations to benthic, pelagic or omnivorous feeding modes (Langerhans, 2008).

Empirical studies across the Gulf of Guinea consistently demonstrate that morphometric and meristic variation in estuarine fishes is strongly linked to salinity gradients, habitat complexity, and spatial environmental heterogeneity. Populations inhabiting upper, low-salinity reaches often differ significantly in body proportions and fin structures from conspecifics in more marine-influenced zones (Asuquo &

Ifon, 2022; Otogo *et al.*, 2025). These variations may reflect both genetic differentiation and environmentally induced phenotypic plasticity, underscoring the importance of morphomeristic analyses for understanding population structure, stock identification, and adaptive responses in estuarine fisheries.

Biology and Ecological Traits of *Piaractus mesopotamicus*
Piaractus mesopotamicus (Holmberg, 1887), commonly known as pacu, is a large-bodied characiform fish belonging to the family Serrasalminidae. It is naturally distributed within the Paraná-Paraguay River Basin of South America, where it inhabits rivers, floodplains and seasonally inundated wetlands that is characterized by pronounced hydrological variability (Nelson *et al.*, 2016). The species exhibits a characteristically deep and laterally compressed body, a morphology that enhances stability and maneuverability in slow-flowing and structurally complex floodplain habitats.

Ecologically, *P. mesopotamicus* is an opportunistic omnivore with a highly flexible diet, consuming fruits, seeds, macrophytes, invertebrates and detrital material depending on seasonal availability. This trophic plasticity is supported by its strong molariform dentition and well-developed jaw musculature, which allow efficient processing of both plant and animal matter (Abimorad *et al.*, 2007). Such feeding versatility reduces dependence on specific food resources and enhances resilience to environmental fluctuations, a key advantage in dynamic aquatic systems.

The species is also distinguished by robust fin structures and a powerful caudal peduncle, which contribute to effective swimming performance and burst acceleration. These traits facilitate foraging, predator avoidance and migration across heterogeneous habitats, particularly during flood pulses. Physiologically, *P. mesopotamicus* demonstrates a relatively broad tolerance to variations in temperature, dissolved oxygen and water quality, attributes that have supported its successful domestication and expansion in aquaculture across tropical and subtropical regions (Kubitza, 2019).

Outside its native range, these biological and ecological traits may confer a capacity for adjustment to novel environments, including estuarine systems. The deep-bodied form and fin robustness can enhance stability under variable flow regimes, while dietary flexibility allows exploitation of diverse estuarine food webs. Although primarily a freshwater species, evidence from cultured and introduced populations suggests a degree of tolerance to low and fluctuating salinities, indicating potential for phenotypic adjustment in brackish conditions. Collectively, these is a characteristics position of *P. mesopotamicus* as a species with considerable adaptive potential, making it a suitable model for investigating morphological variation and ecological plasticity in estuarine environments beyond its native distribution.

Introduction and Establishment in Non-native Estuarine Systems

The global translocation of *Piaractus mesopotamicus* beyond its native South American range has largely been driven by the rapid expansion of aquaculture and the search for hardy, fast-growing species with high market acceptance. In recent decades, introductions of the species have been documented in parts of Africa and Asia, primarily through intentional stocking for aquaculture and in some cases, accidental escape into natural water bodies (Mikkola, 2024). These translocations reflect broader global trends in aquaculture diversification aimed at improving production efficiency and enhancing food security.

In Nigeria, growing interest in *P. mesopotamicus* is closely linked to efforts to diversify farmed fish species and reduce fishing pressure on heavily exploited native stocks, particularly in inland and coastal regions. Its rapid growth rate, omnivorous feeding habits and tolerance to a wide range of culture conditions make it attractive to farmers seeking alternatives to traditional species such as *Clarias gariepinus* and *Oreochromis niloticus*. Nevertheless, the establishment of non-native species in open systems raises important ecological questions. Information on the species' survival, dispersal and ecological integration within estuarine environments of the Gulf of Guinea remains sparse, especially with respect to its interactions with native fish assemblages and responses to fluctuating salinity and hydrodynamic conditions.

Understanding how introduced populations adjust to novel estuarine environments is critical for both aquaculture management and biodiversity conservation. Morphomeristic analyses provide a cost-effective and robust approach for assessing patterns of adaptation, population structuring and potential ecological impacts of introduced fishes. Variations in morphometric proportions and meristic counts between native and non-native populations can serve as early indicators of environmental adjustment or population differentiation. Such differences may arise from founder effects associated with limited initial broodstock, environmentally induced phenotypic plasticity or the early stages of genetic divergence under new selective pressures (Leo *et al.*, 2020).

Within the context of the Gulf of Guinea estuaries, morphomeristic studies of *P. mesopotamicus* can therefore contribute valuable baseline information. They can help elucidate whether introduced populations are exhibiting localized morphological shifts linked to estuarine conditions, inform risk assessments regarding ecological compatibility, and support evidence-based decisions on the sustainable use and management of non-native species in Nigeria's increasingly stressed coastal ecosystems.

Applications in Fisheries Management and Aquaculture Development

Morphomeristic data play a critical role in fisheries management by providing reliable, cost-effective tools for stock identification, population discrimination and assessment of environmental influences on fish phenotypes. By detecting spatial and temporal variations in body proportions and meristic counts, morphomeristic analyses enable managers to delineate distinct stocks within a species, thereby supporting the development of stock-specific management measures such as size limits, closed seasons and spatially targeted conservation strategies (Jawad *et al.*, 2022). In estuarine systems, where environmental conditions fluctuate markedly, repeated morphomeristic monitoring can also serve as an indirect indicator of habitat quality and ecosystem change, helping to track the impacts of pollution, habitat modification, and climate-driven alterations on fish populations.

In aquaculture development, morphomeristic traits are equally valuable. They provide practical criteria for broodstock selection by identifying individuals with desirable body conformation, growth-related traits and structural robustness. Consistent morphometric evaluation can aid in strain characterization and improvement programs, particularly where selective breeding is being implemented to enhance growth performance, feed efficiency or environmental tolerance. Additionally, morphomeristic markers are useful for distinguishing between strains, hybrids

and pure lines, thereby supporting quality control in hatchery operations and reducing the risk of unintended introgression (Kubitza, 2019; Kumar *et al.*, 2020).

Within the West African context, the application of morphomeristics is especially significant. Limited access to advanced molecular and genomic tools, coupled with financial and infrastructural constraints, often restricts large-scale genetic monitoring of fish stocks. Morphomeristic approaches therefore offer a practical and accessible alternative for baseline assessment, routine monitoring and comparative studies of both native and introduced species. When integrated with ecological and environmental data, these methods can provide robust insights into population structure, adaptive responses and management needs, supporting sustainable fisheries and responsible aquaculture development in the region's diverse and increasingly pressured aquatic ecosystems.

Research Gaps and Future Directions

Despite extensive morphomeristic research globally, significant gaps remain for *P. mesopotamicus* in West African estuaries. These include limited baseline data, insufficient integration of environmental variables, and underutilization of multivariate approaches. Addressing these gaps is essential for sustainable fisheries management, aquaculture development, and conservation planning in the Gulf of Guinea.

CONCLUSION

Morphomeristic approaches remain indispensable tools in fisheries science, particularly in data-limited regions such as West Africa. For *Piaractus mesopotamicus*, integrated morphometric and meristic analyses provide critical insights into adaptation, population structure and management potential in estuarine systems of the Gulf of Guinea. Strengthening morphomeristic research on introduced species will support sustainable exploitation, responsible aquaculture expansion and ecosystem-based management in tropical estuaries.

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